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Review Article

Electricity Generation Designs From Ocean Vertical Wave Motions: A Review

JSV Siva Kumar[1], Hemanthakumar Chappa[2]

[1,2]*Department of EEE, GMR Institute of Technology, Rajam, Andhra Pradesh, India.*

[1]*Corresponding Author : hemanthkumar.ch@gmrit.edu.in*

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Abstract - *The increasing demand for clean, sustainable energy sources has driven research into innovative technologies that minimize environmental impact while fulfilling global energy needs. This study investigates the viability of harnessing ocean wave motion as a sustainable electricity source. Wave energy, abundant across approximately 71% of the Earth's surface, presents a largely untapped potential. This work identifies their respective effectiveness, scalability, and environmental implications through a comparative analysis of various wave energy conversion methods—including oscillating water columns, point absorbers, and attenuators. Key findings reveal that point absorbers offer greater efficiency in energy capture while oscillating water columns demonstrate superior environmental compatibility. Challenges such as geographical variability of wave resources, irregular wave patterns, and grid integration complexities are highlighted as critical factors for practical deployment. Overall, the study confirms that ocean wave energy holds significant promise as a renewable resource, provided that technological and infrastructural hurdles are addressed. This paper comprehensively reviews ocean vertical wave motion-based electricity generation, examining primary wave energy converter (WEC) technologies such as oscillating water columns, point absorbers, and attenuators. Key findings highlight the transverse flux permanent magnet generator's superior performance, potential power outputs of up to 90% operational time, and ecological benefits. The paper outlines selection criteria for WECs' comparative generator performance and proposes future directions for hybrid integration and optimized control strategies.*

Keywords - *Sustainable energy, Wave energy conversion, Ocean wave motion, Renewable energy technologies, Vertical wave.*

1. Introduction

Recent advancements in engineering and design have led to the creation of innovative systems for harnessing ocean wave energy. These systems typically utilize a combination of mechanical, hydraulic, and electrical components to convert and transmit the energy generated by vertical wave motion. Additionally, hybrid systems may be employed to further enhance efficiency and reliability. Combining wave energy with renewable sources like wind or solar is being explored to enhance energy reliability. Ensuring stability is crucial in the extraction of wave energy. According to the principle of energy conservation, devices extracting energy from waves must interact to diminish the existing wave energy in the sea. This is achieved by generating waves that interfere destructively with the sea waves. A good wave absorber should also function as a good wave generator. This is advantageous in systems like heaving-float setups, where practically all the volume interacts with the waves. To describe the mathematical aspects of wave-energy extraction, let's simplify by considering a body oscillating in a single mode, such as the heave mode. We will assume small amplitudes for waves and oscillations, making linear theory applicable. In cases where latching control is involved, the system is not time-invariant. Therefore, instead of analyzing system dynamics in the frequency domain, it is more effective to utilize time-domain analysis.

Figure 1 provides an overview of the various stages of converting wave energy. It illustrates the diverse methods of extracting power from waves, including pneumatically, hydraulically, and mechanically. The mechanical interface is crucial in converting slow rotational or reciprocating motion into high-speed rotational motion, facilitating connection to a standard rotary electrical generator. The focus here is on the mechanism required to convert wave energy into electricity, as most components in the generation system remain largely unchanged once transformed into electrical energy. While linear generators are being tested, they are not yet widely implemented in developed Wave Energy Converters (WECs). Among various types of linear generators investigated for Advanced Wave Energy Converters (AWS WECs), the transverse flux permanent magnet generator emerges as a promising candidate due to its higher power density and efficiency. The use of permanent magnet synchronous generators presents an intermediate option, while employing induction generators necessitates a specific mechanical Power Takeoff (PTO) system that introduces additional losses, thereby affecting the overall efficiency of the WEC [1, 2].

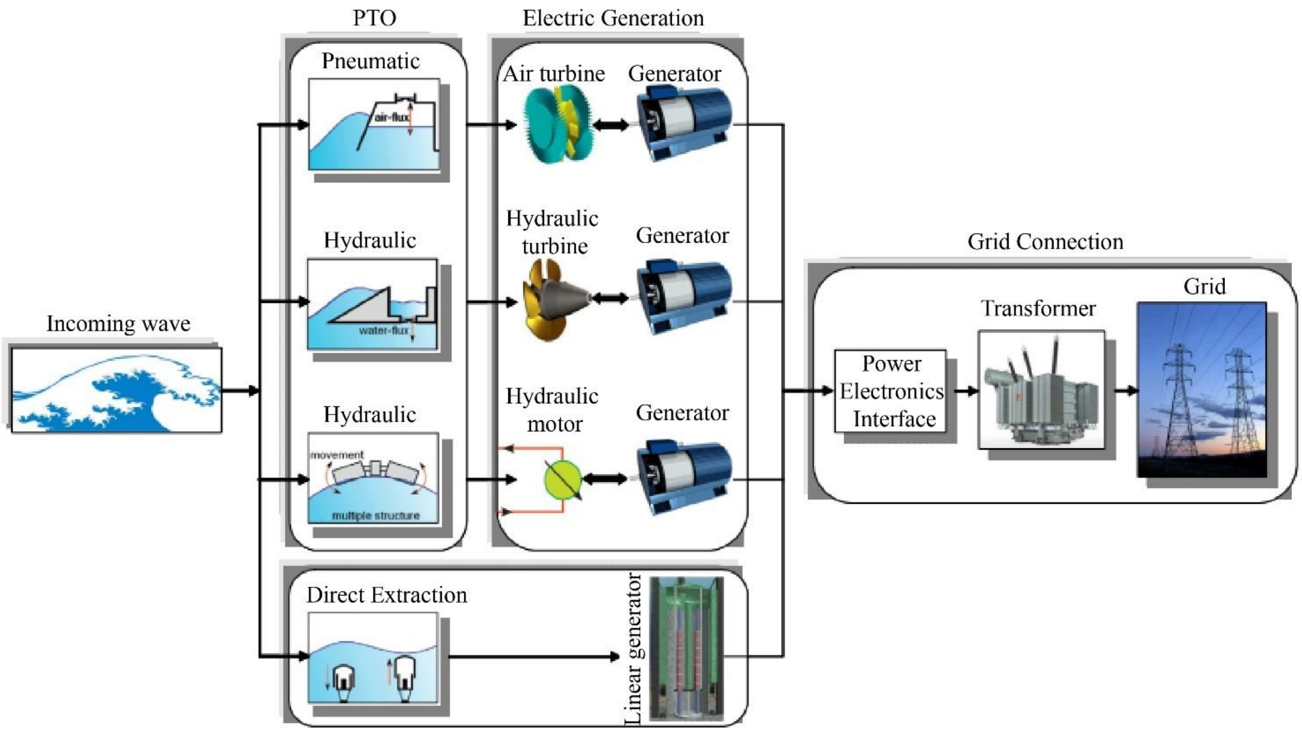

Fig. 1 Different types of conversions [1]

Wave resources are typically quantified regarding power per wavefront meter, representing the wave crest's length [3].

$$\mathrm{P}_{\mathrm{w_f}} = \frac{1}{8\pi(\rho g^2 A^2 T))}$$
$$P_{w_f} = \frac{1}{8\pi(\rho g^2 A^2 T))} \mathrm{P}_{\mathrm{w\_f}} = \frac{1}{8\pi(\rho g^2 A^2 T))} \quad (1)$$

This equation relates to wave characteristics, where ρ represents water density (around 1000 kg/m³), g is the acceleration due to gravity, A stands for wave amplitude, and T denotes wave period. Alternatively, wave power per meter crest length (Pw_mcl) can be used to describe these characteristics [3].

$$\mathrm{P}_{\mathrm{w\_mcl}} = \frac{1}{32\pi(\rho g^2 H^2 T)} \; P_{w\_mcl} = \frac{1}{32\pi(\rho g^2 H^2 T)} \quad (2)$$

It is important to highlight that the wave height, denoted as H, equals twice the wave amplitude, represented by 2A. The potential of ocean vertical wave motion as a renewable energy source and the development of innovative designs to efficiently convert this motion into electrical power have been explored in this work. It highlights the dynamic nature of ocean waves, which are powered by wind and gravitational forces, and emphasizes their cleanliness and minimal environmental impact compared to traditional fossil fuels. The main challenge lies in effectively capturing and converting the immense power of ocean waves into electricity reliably and cost-effectively [4]. Apart from wave characteristics, it is also crucial to explore ocean energy resources as they have the potential to generate renewable and sustainable energy. A brief description of ocean energy resources is shown in section 2.

Wave energy has significant global potential, with empirical studies estimating that the theoretical worldwide wave energy resource is approximately 29,500 TWh per year (IRENA, 2014), which is more than the current global electricity demand. According to the US Department of Energy (DOE), the usable wave energy resource along the US coast alone is estimated to be around 1,170 TWh per year, nearly one-third of total US electricity consumption. A study by the European Commission indicates that Europe's Atlantic coastline could provide up to 280 TWh per year, accounting for about 7% of the European Union's current electricity demand. Experimental deployments like the WaveRoller project in Portugal have demonstrated average power outputs of 300–500 kW from near-shore devices. These figures underline the enormous potential of wave energy, particularly when deployed in high-energy coastal regions such as the North Atlantic, Pacific Northwest (USA), and parts of Australia.

This paper addresses these critical gaps by presenting a unified review that evaluates various wave energy conversion technologies, compares generator types based on performance criteria, explores ecological and grid integration challenges, and identifies key future research directions. The novelty of this review lies in its multidisciplinary coverage, making it a valuable reference for academic researchers and system designers.

The novelty of this work lies in its multidimensional approach that combines technological, ecological, and economic perspectives in a single study. Unlike earlier works such as [4], which focused primarily on theoretical device classifications, or [3], which emphasized electrical interface analysis, this review integrates performance data of generator types, ecological concerns, and hybrid system potential into a comprehensive framework. This holistic approach enables more informed decision-making for WEC selection and deployment strategies, offering actionable insights for researchers, designers, and policymakers alike.

2. Ocean Energy Resources

2.1. Ocean Currents

Ocean currents fall into two main categories: marine currents and tidal currents. Earth's rotation heavily influences these currents and demonstrates high predictability. Marine currents, like the Gulf Stream in the Atlantic, stem from differences in water temperature across the ocean [3, 6, 7]. Warm Equatorial water moves towards the poles, cools, sinks, and eventually circulates back, forming a cyclic conveyor belt called the thermal cycle. This cycle experiences periodic speed fluctuations over approximately a decade. Tidal currents, however, are distinct from marine currents as they result from the gravitational pull of the Moon on the ocean. Tides occur semi-diurnally (twice daily), diurnally (once daily), or in a 14-day cycle, depending on location. Unlike the consistent flow of marine currents, tidal currents start unidirectionally and then reverse direction at the end of the cycle. Prototype marine current generators, similar to hydroelectric systems or underwater wind turbines, have been deployed in Europe and the US.

2.2. Wave Energy

Ocean waves originate from converting solar energy to wind energy, which then transfers to water. This wave energy, capable of travelling long distances with minimal loss, results from the interaction between solar energy, wind, and water. Waves offer a reliable energy source with predictable power intensity, forecastable several days in advance, surpassing wind or solar energy predictability [3, 6-9].

Wave energy is typically measured in kilowatts per meter of a wave crest, the standard quantification unit. The ocean contains an estimated 8,000-80,000 TWh/yr or 1-10 TW of wave energy, with each wave crest transmitting an average of 10-50 kW/m.

2.3. Wave Climate

Assessing a location's potential for wave energy development requires studying parameters like wave height, length distributions, and average water depth. These factors define the area's wave climate, the basis for calculating its wave power levels. Typically, regions along the western edges of continents experience higher wave energy levels due to prevailing west-to-east winds. Additionally, wave energy decreases upon reaching the shore due to frictional losses with the coastline [11]. Notably, average wave power follows cyclical patterns, with winter energy levels potentially six times higher than summer's.

2.4. Energy Converting Waves

Wave Energy Converters (WECs) are designed to harvest energy from the shoreline to deeper offshore waters. These devices are generally categorized based on installation location and Power Takeoff (PTO) system [6, 14]. Installation locations include shoreline, near shore, and offshore areas. In this context, most devices fall into one of six types: Attenuator, Point absorber, Oscillating wave surge converter, Oscillating water column, Overtopping device, and Submerged pressure differential.

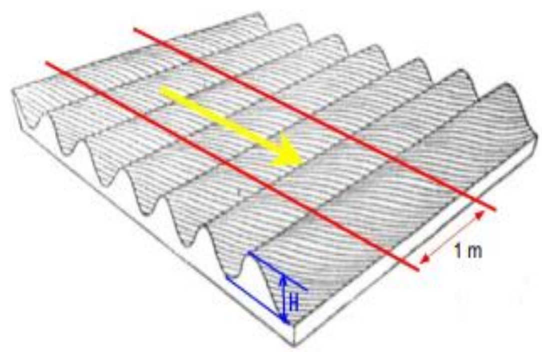

Fig. 2 Wave dimensions [1]

Name	*Description*	*Units/Value*
SWL	mean *s*ea*w*ater *l*evel (surface)	
$E_{density}$	wave energy density	J/m^2
$E_{wavefront}$	energy per meter wave front	J/m
$P_{density}$	wave power density	W/m^2
$P_{wavefront}$	power per meter wave front	W/m
h	depth below *SWL*	m
ω	wave frequency	rad/s
λ or L	wavelength = $gT^2/(2\pi)$	m
ρ_{water}	sea water density	1000 kg/m^3
g	gravitational constant	9.81 m/s^2
A	wave amplitude	m
H	wave height	m
T	wave period	S
C	celerity (wave front velocity)	m/s

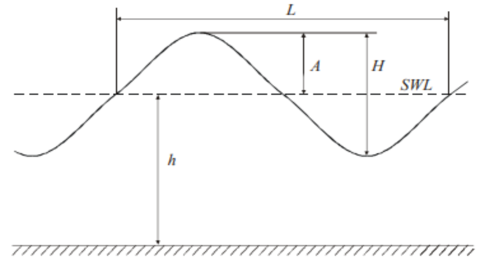

Fig. 3 Wave nomenclature [5]

3. Energy Wave Calculations

3.1. Overview

Computing the forces acting on a Wave Energy Converter (WEC) and the wave power available during the design phase is essential. Comprehending these variables is imperative [10] to dimension a WEC according to the intended energy yield. This section explores the fundamental elements of these computations, clarifying the many principles, parameters, and corresponding values.

Energy and Power Density: The average energy flow passing along a vertical plane parallel to the crest of a wave is referred to as energy density. The wave's power density, or energy per wave period, can be calculated by dividing the energy density by the wave period [3, 2-4].

$$E_{density}=\rho_{water}\text{g}H^2/8 \;\; =\rho_{water}\text{g}A^2/2 \tag{3}$$

$$P_{density=}E_{density}/2=\rho_{water}\text{g}H^2/(8\text{T})=\rho_{water}\text{g}A^2/(2\text{T}) \tag{4}$$

3.2. Power Per Meter of Wave Front

The power per meter of wave front, or wave crest, is commonly used to characterize a wave resource. Multiplying the energy density by the wavefront velocity yields this value.

$$P_{wavefront}=\text{C}.E_{density}=\rho_{water}\text{g}H^2/(16\omega)=\rho_{water}\text{g}A^2/(4\omega) \tag{5}$$

As shown in figures, wave period and amplitude impact wave power density and power per wavefront. 3 and 4. Recognizing Energy Variations with Depth: It is essential to precisely calculate the wave power at the intended [11, 6, 12-15] working depth when developing an underwater Wave Energy Converter (WEC). Wave power typically decays at a rate of -2πd/λ below sea level, where 'd' is the depth below the still water level (SWL). This decay is exponential. This rule applies only to water depths greater than half the wave's wavelength (λ/2)...

$$\text{E(d)} \;=\; e^{(-2\pi\text{d}/\lambda)} \cdot \text{E}(SWL) \tag{6}$$

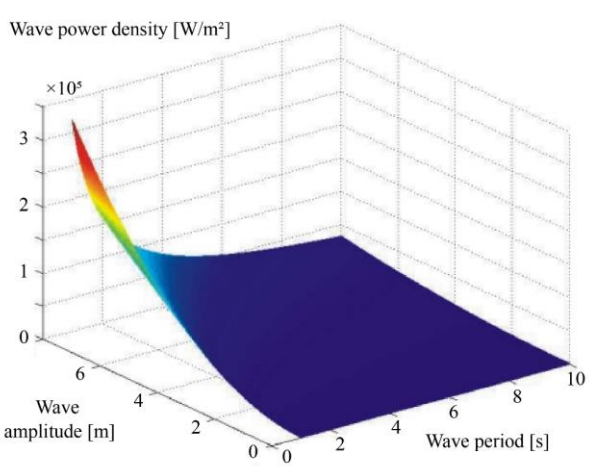

Fig. 4 Density of waves [3-5]

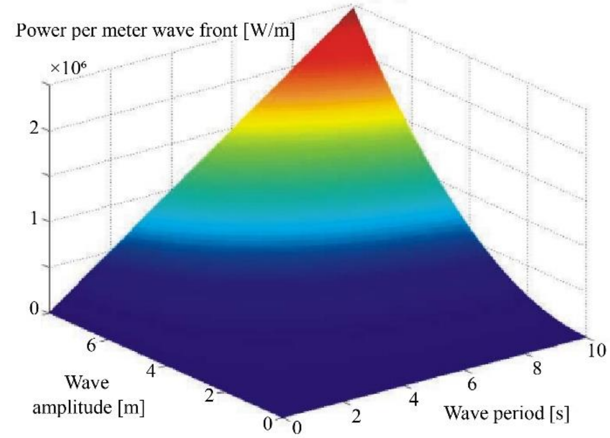

Fig. 5 Wavefront power per meter [3, 5, 6]

3.3. Using Force and Vitality in Every Direction

Wave Energy Converters (WECs), known as "point absorbers" or "buoy-types", are engineered to capture wave energy from multiple directions at a single oceanic point [16, 17]. This technology features an underwater buoy that moves vertically in response to passing wave crests and troughs, resulting in a linear motion that mirrors the wave's mass fluctuations. The motion of this buoy can be accurately described by Newton's second law of motion. Here, the mass 'm' of the displaced water is calculated as ρ_waterHA_float, where 'A_float' denotes the float's surface area, and gravity is the acceleration force.

$$F_{water} = \text{m a(} \; \rho_{water}\text{H}A_{float}\text{)g}. \tag{7}$$

P_generated, the power produced and transferred to the float, is calculated by multiplying the float's velocity (V_water) by the force applied by the water. By dividing the stroke length (L_Stroke) by half of the wave period, this velocity is [3] obtained.

$$P_{generated} \;\; = F_{water}(2L_{Stroke}/T)[3] \tag{8}$$

Water can be used to drive a hydro turbine or piston through a hollow tube that is immersed vertically, transferring power. The force (F_generated, in Newtons) applied to the piston inside the tube can be used to calculate the power produced in this configuration [18]. The desired power output (P_desired) and the piston stroke length are considered while calculating this force...

$$F_{generated}=P_{desired}\text{T}(2L_{Stroke}/T)[3] \tag{9}$$

Harnessing Power and Energy through Wave-Induced Air Pressurization: Wave Energy Converters (WECs) of the "oscillating water columns" (OWCs) type operate similarly to wind turbines by utilizing wave-induced air pressurization. The power generated by the airflow within the OWC outlet depends on various factors, including the airflow velocity at the turbine (V_air, in meters per second), the turbine's area (A_duct, in square meters), the pressure at the turbine (P_air, in Pascals), and the air density (ρ_air, in kilograms per cubic meter) [17]. This power consists of two components: (i) the kinetic energy of the airflow, given by V_air³A_ductρ_air/2, analogous to wind turbine principles, and (ii) the air pressure term, P_airV_airA_duct, which is unique to this application.

$$P_{OWC}=(\rho_{air}+v_{air}^{2}/2)v_{air,}A_{duct}[3] \quad (10)$$

3.4. Electrical Generators for Converting Wave Energy

In all Wave Energy Converters (WECs), a mechanical interface converts slow rotational or reciprocating motion into high-speed rotational motion compatible with conventional rotary electrical generators. Although linear generators (direct drive) are promising, they are not yet commonly used in the most advanced WECs [20]. Research on various linear generators for AWS wave energy converters suggests that the transverse flux permanent magnet generator is an excellent candidate due to its higher power density and efficiency.

Induction generators, in contrast, require a specific mechanical power takeoff (PTO) system that introduces additional losses, reducing the overall efficiency of the WEC. These losses can be avoided with a direct drive approach, but significant mechanical engineering challenges remain, especially regarding the size and weight of integrating direct drive systems into WECs [2].

The greatest locations for harnessing wave power are in the north and south temperature zones. Wintertime brings the greatest winds in these zones. The predominant western winds that blow at these latitudes on both hemispheres cause increased wave activity between 30° and 60° [23]. Power per meter of wave front (wave crest length) is the usual unit of measurement for describing a wave resource [6].

$$AT\ w\ f\ =\ \rho\,\pi \quad (11)$$

Where g is gravity acceleration, A is amplitude, T is wave period, and ρ is water density (about 1000 kg/m3). The wave power per meter crest length (Pw_mcl) can also be explained.

$$PgHTwmcl\ =\ \rho\,\pi \quad (12)$$

4. Existing Methodologies

4.1. Classifying Wave Energy Equipment

There is a close relationship between wave energy devices (WEDs) and wave energy converters (WECs). When we talk about a wave energy device (WED), we usually mean a physical structure that uses the mechanical power of the ocean waves to drive electrical generators to produce electricity. On the other hand, a wave energy conversion system uses a converter known as a WEC. It converts wave-like irregular mechanical energy into regular mechanical motion, either translational or rotational [21].

While linear electrical generators are powered by translational motion, turbines often drive rotating electrical generators. The wave energy conversion principle cannot be realized without the WED [22]. Various WED kinds are classified according to operational ideas like oscillating water columns or the position of the location of the device (near-shore, onshore, fixed, floating, submerged) and orientation.

Various WED types are discussed, each suited for specific conditions like water depth and wave height. Onshore refers to coastal regions with water depths around 10-15 meters, where waves can reach heights of up to 7.8 meters. Near-shore areas have intermediate depths ranging from 15-25 meters. These distinctions also consider whether the waves are in the type and location of wave energy converters, which are affected by whether the water is deep, moderate, or shallow.

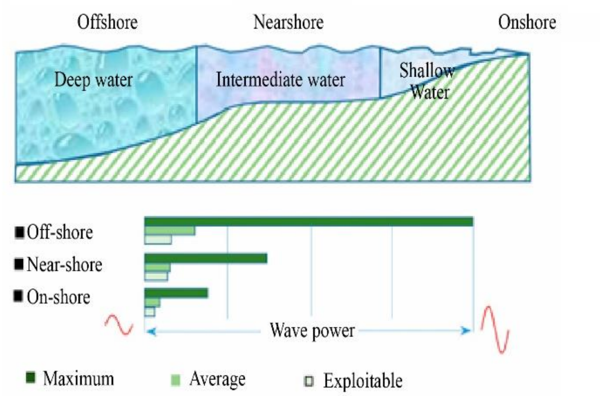

Fig. 6 Where the wave energy converter system is located in the ocean [4]

Deep-water zones, with ocean depths exceeding fifty meters and wave heights up to thirty meters or more, are home to offshore territories. Energy waves tend to lose density as they move towards onshore and near-shore regions, as shown in Figure 1. Therefore, constructing offshore wave power devices is [4] generally easier than building onshore or near-shore devices [23]. This is because constructing large structures in intermediate and shallow waters, where waves often break violently and almost touch the seabed, is extremely challenging. Coastal structures in these areas are more susceptible to failure than those in deep water despite the potential nonlinearity of waves. The last thirty years have seen a significant increase in the use of wave energy devices in energy production. These devices come in various forms, including point absorbers, bulge wave converters, oscillating wave surge converters, overtopping or terminator devices, and oscillating water columns. Point absorbers are popular among researchers because they are affordable and can produce energy [24]. Utilizing a single point where one component is almost completely still, and another is almost at the surface of the water, point absorbers leverage the action of waves by having moving pieces whose horizontal dimensions are smaller than their vertical ones. In order to generate electricity, this arrangement enables the capture of wave energy by perpendicular motion, which powers a linear generator. Ocean Power Technologies' "Power Buoy," shown in figure, is a prominent example of a point absorber.

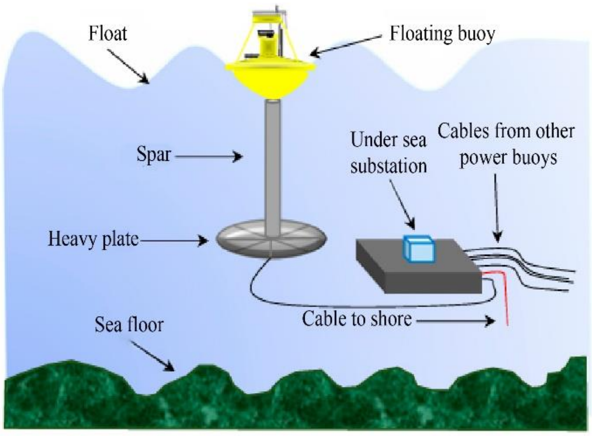

Fig. 7 shows a schematic diagram of a wave energy converter (WEC) with a point absorber [5]

A big construction intended to collect saltwater is the overtopping wave power device, sometimes called the terminator. When waves enter the channel through a hole, water enters a turbine connected to a revolving electrical generator. Potential energy gradually transforms into kinetic energy, and the turbine turns both forms of energy into electrical energy. The Wave Dragon is one instance of an overtopping wave power gadget [25].

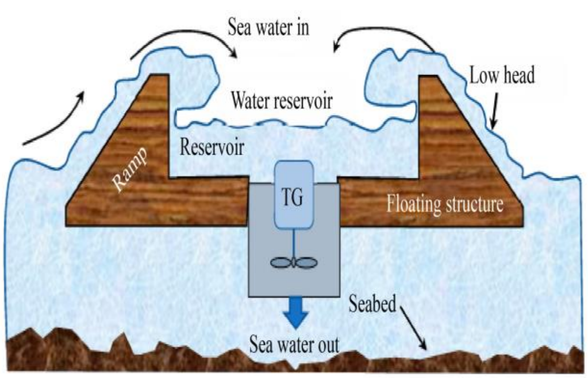

Fig. 8 Water column that rotates

The overtopping device is illustrated in Figure 8 [5]. A device that turns the energy of ocean waves into electricity is called the Oscillating Water Column (OWC). Usually, it is placed close to the bottom and in proximity to rocky areas. A rise in water level and the production of high air pressure are caused by the waves compression and decompression of the interior air as they reach the device. An electric generator is attached to a turbine driven by the pressure differential, which is greater inside the chamber [5] than in the surrounding air. A rush of outside air enters the chamber when the wave recedes because the internal air pressure falls below atmospheric pressure [26]. A negative airflow produced by this air inflow helps rotate the turbine, which facilitates the production of energy.

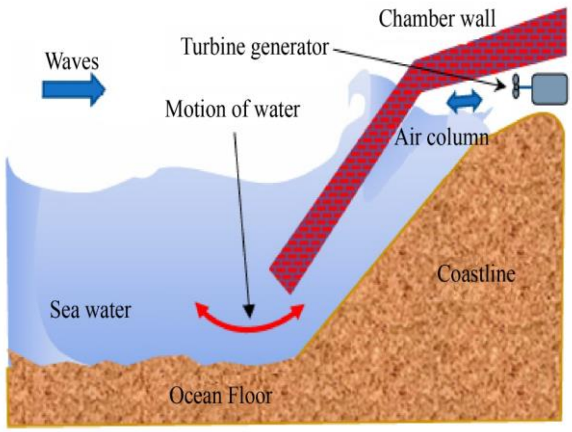

Fig. 9 Diminutors

The entire oscillating water column structure is shown in Figure 10 [5]. An attenuator, often called a surface attenuator wave power device, closely tracks the direction of wave flow. The device comprises interconnected pieces, such as bends and main tubes, that respond sequentially to waves that touch each element of the device in turn. A power conversion module is placed within the main tube, which consists of a nose tube, mid tube, and end tube, between two main tubes. Figure 5 shows this arrangement. The Pelamis, manufactured by Pelam, is a well-known illustration of a wave energy converter (WEC) [25].

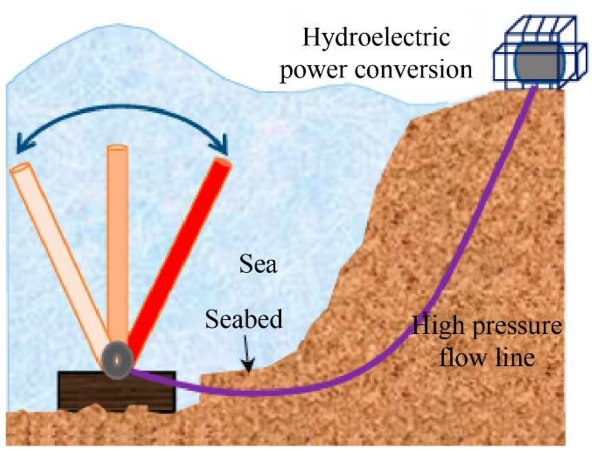

Fig. 10 Device for harvesting attenuator wave energy [5]

Table 1. Comparison of different generators in wave energy conversion

Generator Type	Efficiency	Speed Range	Maintenance Needs	Suitability for WECs	Comments
Induction Generator (IG)	Moderate	Narrow	Low to Moderate	Good for fixed-speed systems	Rugged and inexpensive; limited by fixed grid frequency without converters
Synchronous Generator (SG)	High	Wide (with converter)	Moderate to High	Suitable for variable-speed WECs	Offers grid synchronization and high power quality; requires excitation system
Permanent Magnet Synchronous Generator (PMSG)	High	Wide	Low	Excellent for direct-drive WECs	High efficiency, compact size, no need for external excitation
Switched Reluctance Generator (SRG)	Moderate	Very Wide	Low	Emerging for harsh environments	Simple construction, fault-tolerant, good for submerged WECs
Linear Generator	Moderate	Direct linear motion	Moderate	Ideal for point absorber WECs	Eliminates the need for mechanical transmission; low-speed operation

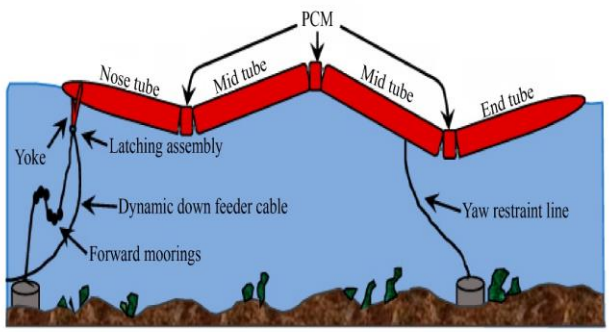

Fig. 11 Oscillating wave surge converter floating gadget [4]

In order to generate energy, the hydraulic cylinder uses high-pressure oil to drive hydraulic motors, which in turn power an electrical generator in response to wave motion. The oscillating motion of ocean waves is harnessed using Oscillating Wave Surge Converters (OWSC), a kind of Wave Energy Device (WED). Usually found at the bottom of the ocean, these instruments are immersed in deep water.

As seen in Figure 6, one [4] popular form has a pendulum arm and flap in the centre of the apparatus that moves in response to waves. Using this motion, water is pumped to a hydraulic power converter, which powers a generator to produce electricity [28]. The Sea Oyster, sometimes known as the Wave R, is one such gadget.

Usually, submerged pressure differential devices like the ones shown in figure are positioned at sea level. The float moves up and down over the apparatus due to the passing waves, producing alternating [5] pressure. After that, this pressure is used to drive a linear generator to produce energy or pump fluid through a system. The Archimedes wave swing is one such wave energy converter created especially for efficiently producing power [29].

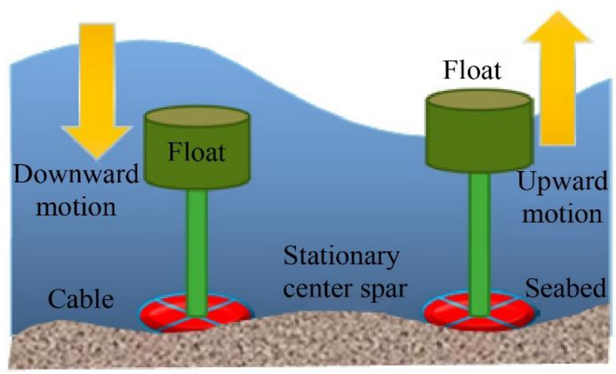

Fig. 12 Rotating mass

Using a submerged pressure differential device, electricity is produced [4]. The rotational mass wave power gadget generates mechanical energy by rolling a heavy physical object (mass) using wave motion. Figure 8 illustrates how this system converts mechanical energy from ocean waves to an electrical generator [4]. Witt Energy, Wello: Penguin, and Enorasy Labs: Robotic Juggler manufactures a few spinning mass wave energy converters.

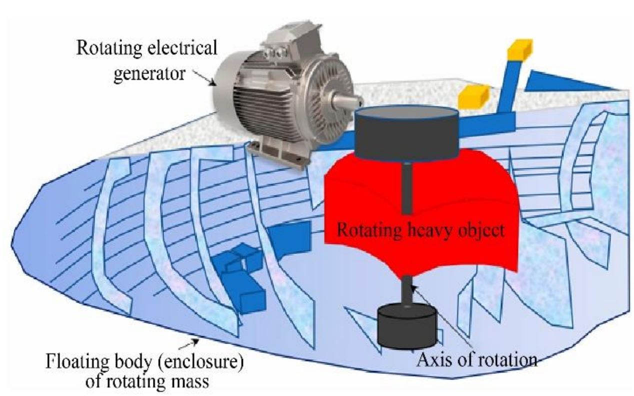

Fig. 13 Bulk head wave energy converter

Checkmate Sea Energy Ltd.'s Bulge Head Wave Energy Converter converts oceanic wave energy into electrical power, also dubbed the Anaconda wave power gadget, which uses cutting-edge concepts. Technology for rotating mass waves [4] is shown in Figure 14. As seen in Figure 10, the purpose of this converter is to use abandoned ocean waves to generate power.

The structure comprises an elastic pipe immersed at low pressure, somewhat below the sea level. Anterior to the main wave, there is a bulge wave formed by the pipe's other side moving in tandem with the passing sea waves, with one side fixed and anchored to the base [29].

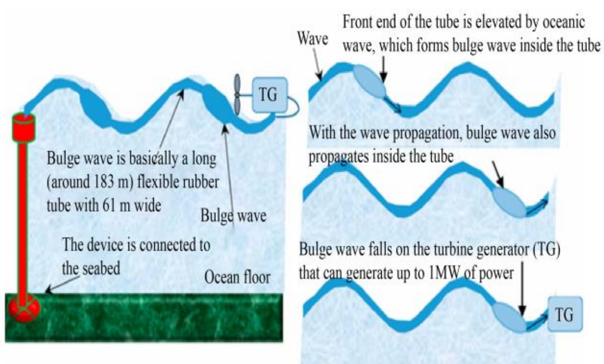

Fig. 14 Bulge wave energy production system [4]

A Turbine Generator (TG) is powered by the energy this technology continuously harvests from the bulge wave. Despite numerous technological demonstrations and studies on individual Wave Energy Converters (WECs), a coherent and comparative framework addressing multiple aspects of wave energy systems is still lacking. Many existing reviews focus on specific device types or theoretical models without integrating real-world generator performance, ecological impact, or control strategies.

This fragmented approach makes it challenging for researchers and developers to select optimal configurations for specific marine conditions. The problem is compounded by the limited understanding of how different generator technologies perform when integrated with wave energy systems, especially in terms of efficiency, cost, and marine adaptability (Table 1 and Table 2).

Moreover, the literature does not cover the ecological implications of deploying these systems at scale and the potential of hybrid systems combining wave energy with other renewable sources. However, they are left for future study or considered as the future scope of this work.

5. Control Technologies

Control technologies are essential to extracting oceanic energy and include various components, including electrical generators, control systems, controller installation sites, wave energy converters (WECs), power conversion techniques, and real-world validation. Oceanic Wave Energy (OWE) engineering has seen a surge in interest due to these technologies.

A number of control strategies, including reactive control, adjustable tuning, adaptive inertia, linear quadrature Gaussian design, and latching control techniques, have been thoroughly investigated. By skillfully controlling reaction forces, these control strategies hope to maximize the production of electrical energy from OWE, efficiently transfer power to the grid, and address challenges in direct drive Wave Energy.

Table 2. Comparison of wave energy conversion methods

Method	Efficiency	Scalability	Environmental Impact	Structural Durability	Cost	Grid Integration	Suitable Site Conditions
Oscillating Water Column (OWC)	Moderate	High	Low to Moderate	High	Moderate	Good	Coastal areas, onshore/offshore
Point Absorber	High	Moderate to High	Moderate	Moderate	High	Good	Deep waters, high wave energy zones
Attenuator	Moderate	High	Moderate	Moderate	High	Moderate	Offshore, parallel to wave direction
Overtopping Device	Low to Moderate	Moderate	High (habitat alteration)	High	High	Moderate	Coastal zones with high tidal ranges

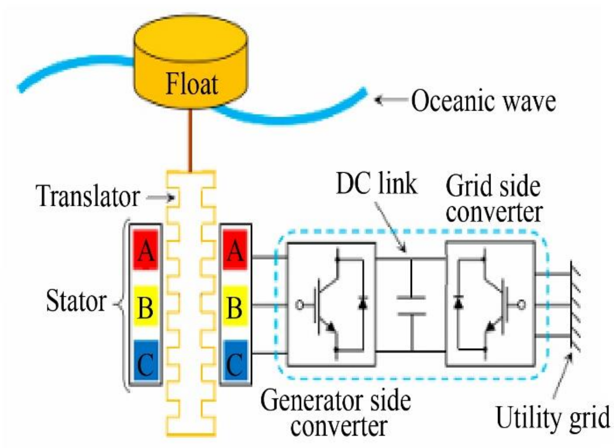

Fig 15. Direct drive representation system WEC [4]

Devices (WEDs) with adjustable load criteria. Despite the complexities associated with control systems, sustainability concerns, and the costs involved in WEDs, advancements in control technologies, particularly reactive control methods, show promise in maximizing OWE extraction without relying heavily on precise wave forecasting. One example of how well-designed control systems can optimize OWE harvesting is creating a centralized model predictive control (MPC) methodology, which effectively controls WECs in an array configuration. In order to improve the effectiveness and performance of maritime energy extraction systems, several control concepts and technologies are essential.

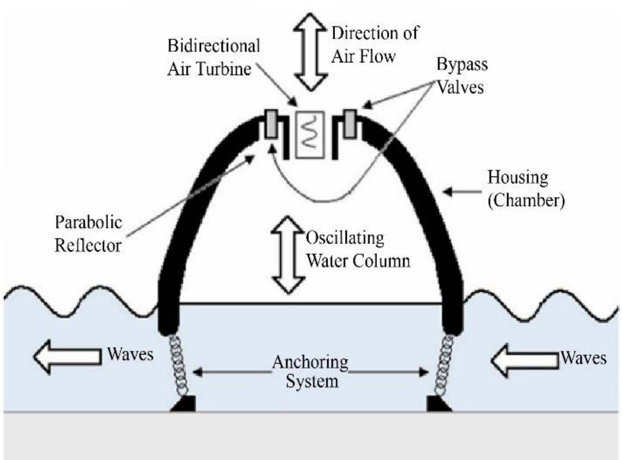

Fig. 16 Overall conversion

In one particular instance, a control system designed for a range of Wave Energy Converters (WECs) showed strong efficacy when compared to decentralized control schemes and restrained forces controllers, especially when controlling erratic and regular ocean wave circumstances. For point absorber-based WEDs with floating buoy designs, a different noteworthy control method based on Model Predictive Control (MPC) was developed. Considering practical aspects, this MPC system sought to maximize Oceanic Wave Energy (OWE) harvesting in the power takeoff (PTO) mechanism, like velocity and wavering force. Straight Driven Linear Generator: The grid integration setup with control systems and WEC-based electrical power generation are shown in Figure 16 [26].

The Wave Energy Device (WED) is designed with a direct drive Power Takeoff (PTO) unit with floating body constructions. Ocean wave oscillations cause the float to move linearly, while the PTO system uses the waves' energy to generate power. Next, the voltage that has been generated is fed into a converter called a generator-side power converter.

The static stator, which usually consists of a coil of wires, and the linearly sliding translator are essential components of the PTO unit. The translator moves in a magnetic field with respect to the stator, causing the stator windings to generate voltage. However, because ocean waves oscillate, the translator's movement produces different relative velocities in relation to the stator, which leads to fluctuations in the induced AC voltage's amplitude and frequency.

To stabilize this voltage for integration into the grid, a multistage power conversion process (AC-DC-AC) is used to ensure synchronization with the grid's power needs. A predictive current control concept was proposed to enhance load inductance estimation accuracy, reducing unsteady effects and low electromotive force (EMF) occurrences. A damping [4] force control technique was also developed to address heaving motion and swift operation of WECs across different wave conditions.

An advanced resonance control algorithm was devised for Archimedes wave swing-based WECs, focusing on optimizing both the stiffness and damping forces of the PTO system. Furthermore, latching control, an alternative to reactive control, minimises electrical generator losses by managing energy flow direction, and practically implementing latching control involves predicting oceanic wave properties to regulate float release.

Enhancing proficiency in latching and reactive control methods necessitates considering WEC excursion limitations under irregular wave conditions during control system design. Voltage imbalances may occur due to integrating distributed renewable sources into utility services. The SEAREV is an innovative Wave Energy Device (WED) developed by the LHEEA laboratory at Ecole Centrale de Nantes, integrating multiple components into a single floating unit.

Featuring a wheel with a horizontal rotating axis surrounded by a floating structure, the technology for synchronizing the SEAREV and other oceanic WEDs with the grid is depicted in the figure showcasing a multistage control configuration.

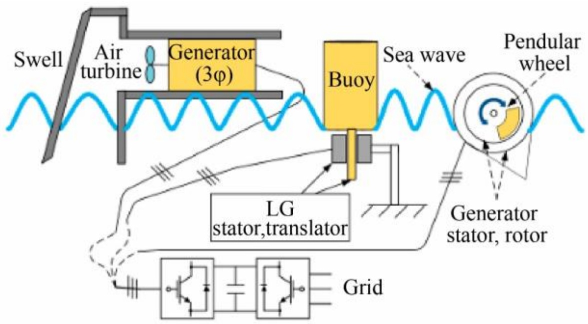

Fig. 17 Offshore OWC device [2]

Figure 17 shows the overall layout of the WEC system based on permanent magnet linear generators (PMLGs): Heaving buoy, SEAREV, and oscillating water column (OWC) [4] There are a number of advantages to using waves as a renewable energy source over other approaches, such as the following:

1. Sea waves have the highest energy density of all the renewable energy sources. Winds are produced by solar energy, which in turn produces waves. An average power flow intensity of 2-3 kW/m2 of a vertical plane perpendicular to the direction of wave propagation just below the water's surface is produced from solar energy intensity, which is normally 0.1–0.3 kW/m2 on a horizontal surface.
2. Minimal adverse effects on the environment when in use. Thorpe provides an estimate of the life cycle emissions of a typical near-shore device along with a detailed description of the possible impact. Offshore devices typically have the least possible impact.
3. The natural seasonal fluctuations in wave energy in temperate regions correspond to the demand for power.
4. Waves have minimal energy loss over long distances. Driven by dominant westerly winds, storms originating on the western side of the Atlantic Ocean will eventually make their way to Europe's western coast.
5. Wave power devices can create power up to 90% of the time, while wind and solar power devices can only do so for roughly 20% to 30% of the time.

5.1. Challenges

1. WECs for offshore converters must be able to endure extremely high wave conditions, which can make maintenance procedures challenging and expensive.
2. The mooring design is an important component, as mentioned above. The WEC alignment for capture optimization places restrictions on the mooring system in addition to the harsh environmental pressures caused by wind, waves, and currents.
3. Significant financial support from governments is required to offset higher development, deployment, and maintenance costs.
4. "Wave" energy conversion machines turn the energy in ocean waves into electrical energy, in contrast to "flow" energy converters, which take energy from the currents in the ocean. Generally speaking, two basic kinds of WECs are distinguished: 1) The turbine type, which attracted the interest of researchers first.

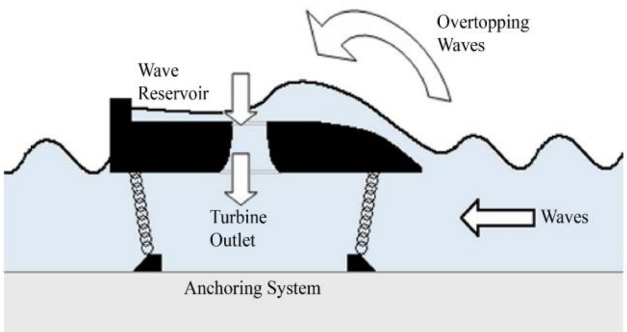

Fig. 18 Overtopping WEC [2]

Recently, there has been heightened focus due to the growing interest in a certain form of buoy. These buoy kinds have been further classified by certain specialists according to their functionality and orientation. Two noteworthy classifications are the overtopping water column (WEC) and the oscillating water column (OWC). Like a wind turbine, the OWC uses wave-induced air pressure. It has an air chamber, or closed containment enclosure, above the water.

Waves change the housing's water level and cause variations in air pressure, which power turbines. Conversely, a hydroelectric dam is analogous to the overtopping WEC in its operation. Water flows towards a hydro turbine through a collector that receives the waves. Generators that generate power are linked to these turbines. Wave energy from waves coming from all directions in the water is captured by the buoy-type WEC, also called a "point absorber" (PA). A positively or neutrally buoyant float immersed vertically is usually what it consists of. A power takeoff mechanism, like a linear generator or piston, is installed on this float to capture wave energy effectively.

Table 3. Utilizable wave energy throughout several european nations [4]

Country	Wave energy Potential (TWh/Year)	
	Offshore	Near-shore
UK	45-65	14-20
Ireland	20-30	7-12
Portugal	12-20	3-7
France	12-18	3-7
Spain	1-15	3-6
Italy	9-16	3-6
Denmark	5-9	2-3
Greece	3-8	1-2
Germany	0.8-1.5	0.3-0.5

Table 4. The entire amount of energy produced using various sources of renewable energy [4]

RESs in (GW)	Year-2017	Year-2018
Hydro Power	1112	1132
Wind Power	541	592
Solar Pv	408	504
BioPower	120	132
Geothermal Power	12.7	13.2
Concentrating Solar Thermal power	4.9	5.6
Ocean Power	0.4	0.4
Total	2199	2366

5.2. The Future Potential of Harnessing Energy from Oceanic Waves

With only a small percentage of their unrealized potential, ocean waves can provide energy for many of the world's requirements. With marine wave energy accounting for around 0.2% of electrical energy, the European Union (EU) is strongly focused on producing power from renewable energy sources (RESs). Wave energy is a top candidate for producing significant electricity because of this century's increased focus on clean and environmentally friendly energy. Its annual energy output capability exceeds other renewable energy sources, with several thousand terawatt-hours to spare. Wave energy thus has much potential to provide our energy needs sustainably. Water has much potential for producing power, especially when it comes to marine wave energy. Compared to non-renewable sources, this can significantly lower carbon emissions, which aligns with the 2003 targets established by the UK government.

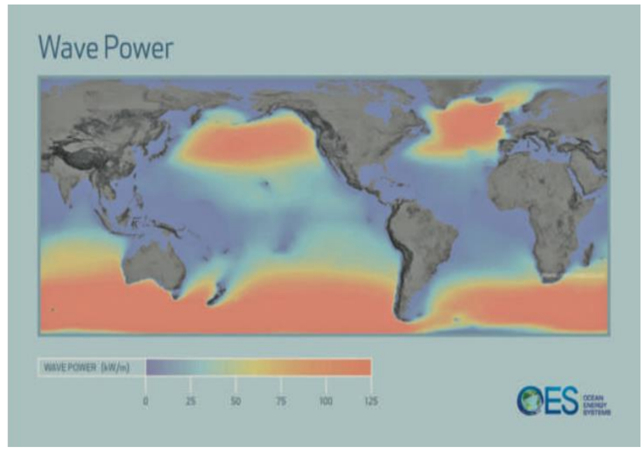

Fig. 19 Wave energy technologies

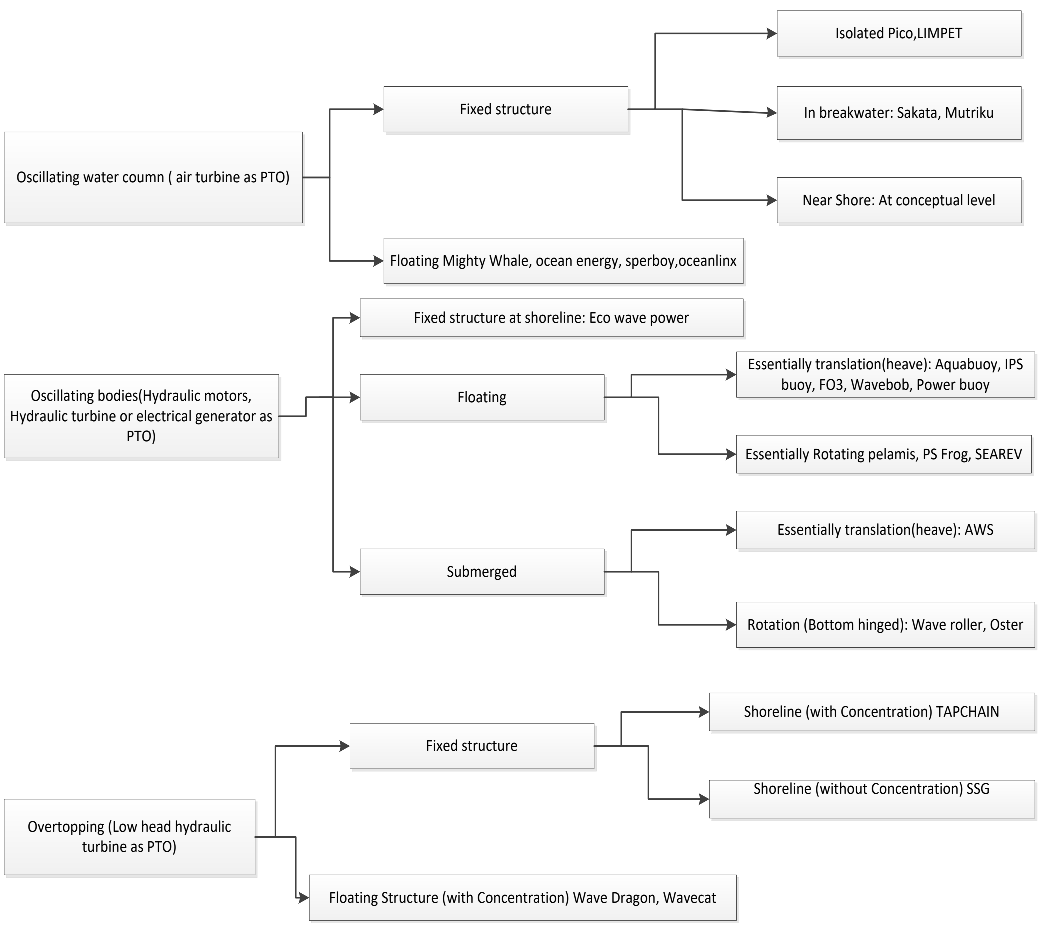

Fig. 20 Distribution of global annual mean wave powers [7]

The United Kingdom is the leader in using oceanic wave energy, accounting for around half of all energy produced in Europe and is expected to increase to 25% of installed capacity in the future. Further latent ocean energies can be utilised, such as ocean thermal energy, marine currents, and tidal energy. Wave energy stands out among renewable sources due to its high availability and predictability, leading to rapid harvest progress over the past decades. It boasts the highest energy production among renewables, operating nearly continuously and surpassing solar and wind energy.

The global potential for wave energy is substantial, estimated at thousands of terawatt-hours per year.Global regions, including the US, China, and Europe, actively explore and implement wave energy projects to reduce energy crises and pollution. The ocean's vast wave energy resources offer a significant opportunity to generate sustainable electricity, potentially mitigating global energy challenges. The available wave energy potential is the primary factor determining the amount of power generated by oceanic waves when employing wave energy devices.

The continent with the largest wave energy resources is Europe, as explained in Section 2. Table 1 summarises the possible wave energies, both offshore and near-shore. Compared to other renewable energy sources that have been used for considerably longer in Europe, ocean power is a comparatively recent newcomer. On the other hand, seawater power produced 0.5 GW of electricity in 2017 and 2018.

5.3. Procedure and Technical Stand

Wave energy converters, or WECs, capture and transform wave energy into electrical power. While extracting energy from waves has been explored since the 1970s, recent advancements have propelled the technology forward. Various WEC concepts are being tested, ranging from full-scale prototypes to commercial demonstrations.As of 2013, there were over a hundred wave energy projects in different stages of development. Looking ahead, the sector aims to deploy demonstrating WECs in small arrays generating around 10 MW of electricity. These arrays will be situated either near shore or in specific testing areas. To transition to full commercialization, further research is needed to optimize the fundamental components of WECs, focusing on reducing costs and improving performance. Additionally, exploring alternative solutions such as hybrid or multiplatform concepts could accelerate the development of wave energy technology. These solutions involve integrating wave energy converters with offshore wind turbines or aquaculture farms, which offers benefits such as shared foundation system costs, reduced operational expenses, and mitigated environmental impact compared to separate installations.

6. Conclusion

In conclusion, the theoretical exploration of electricity generation from ocean vertical wave motion offers valuable insights into this innovative concept's feasibility and potential benefits. Through a comprehensive analysis of the underlying theory, several key conclusions can be drawn:

1. Principle of Operation: The study elucidates the fundamental principles behind harnessing ocean vertical wave motion to generate electricity, highlighting converting mechanical energy into electrical energy through appropriate mechanisms such as oscillating water columns or buoyant systems.
2. Theoretical Efficiency: Based on theoretical models and calculations, the design shows promising efficiency in converting wave energy into electrical power, suggesting a viable approach for renewable energy generation.
3. Sustainability: The concept aligns well with sustainability goals, as it leverages a renewable and abundant resource (ocean waves) without contributing to carbon emissions or environmental degradation, thus supporting global efforts towards clean energy transition.
4. Challenges and Considerations: While the theoretical framework establishes the feasibility of the concept, it also identifies challenges such as technological complexity, material durability in harsh marine environments, and optimization of energy conversion processes, which require further research and development efforts.
5. Potential Applications: The theoretical study highlights potential applications of this electricity generation design in coastal regions, offshore installations, and remote island communities, where access to traditional power grids may be limited or unreliable.
6. Future Directions: To translate theoretical concepts into practical solutions, future research should focus on experimental validations, technological innovations for enhanced efficiency and reliability, economic feasibility assessments, and integration with existing energy infrastructure.

In essence, the theoretical framework presented in this study lays the groundwork for further exploration and development of electricity generation from ocean vertical wave motion, offering a promising avenue for sustainable energy solutions in the context of global energy challenges and climate change mitigation strategies. This conclusion summarizes the theoretical aspects of the electricity generation design from ocean vertical wave motion, emphasizing its potential, challenges, and areas for future research and development.

6.1. Future Scope

While offering a clean and sustainable power source, wave energy systems can pose several ecological challenges that must be carefully addressed. Installing wave energy converters (WECs) may disrupt marine habitats, particularly benthic ecosystems, due to anchoring systems and seabed modifications. To mitigate this, site selection should prioritize areas with minimal ecological sensitivity, and eco-friendly mooring techniques should be employed. Underwater noise generated during construction and operation can disturb marine mammals, potentially affecting their communication and behavior.

Using quieter construction methods, timing activities to avoid sensitive breeding seasons, and incorporating noise-reducing technologies can help reduce this impact. Moving parts and subsea cables may pose collision risks and expose marine species to electromagnetic fields; these risks can be minimized through design optimization, shielding of cables, and monitoring of species behavior near devices.

Furthermore, large-scale deployment may alter wave patterns and sediment transport, influencing coastal erosion and deposition. Detailed hydrodynamic modelling and placement of devices away from erosion-sensitive zones can alleviate such effects. On the positive side, WECs may act as artificial reefs, promoting marine biodiversity, and exclusion zones around them can serve as de facto marine protected areas. With careful planning, environmental impact assessments, and continuous ecological monitoring, wave energy systems can be implemented sustainably with minimal harm to marine ecosystems. While traditional wave energy conversion methods such as oscillating water columns, point absorbers, and attenuators have shown promise in harnessing ocean energy, each comes with inherent limitations related to efficiency, intermittency, or site-specific suitability.

Researchers have begun exploring hybrid technologies that combine wave energy with other renewable sources like wind, solar, and tidal energy to address these challenges and enhance energy reliability. These hybrid configurations aim to balance the variable nature of wave energy by leveraging complementary energy profiles, thereby improving overall system efficiency and stability. For instance, offshore platforms integrating wind turbines and wave energy converters can maximize the use of ocean space while ensuring a more continuous power supply. This evolution toward hybrid systems represents a strategic progression from conventional approaches, aiming to overcome operational and integration challenges associated with standalone wave energy devices.

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